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REMARKS ON THE DOPPLER RADAR MEASURING METHOD FOR INTERIOR BALLISTICS MEASUREMENTS

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REMARKS ON THE DOPPLER RADAR MEASURING METHOD FOR INTERIOR BALLISTICS MEASUREMENTS

G. Schultze

Circuits, methods, and results of the Doppler radar arrangement for measuring interior ballistics are given. An amplifier developed for registering the Doppler shift permits precise evaluation through conversion of sine oscillations into sharply defined impulses, and also interpolation through time- and location-dependent registration signals.

Abstract

This technical communication relates to Report 8/64, which contains /5* results of interior ballistics measurements but which has no description of the measuring apparatus. On this account, this paper presents a description of certain circuits of general interest in the Doppler radar measuring setup. The amplifier developed for recording the Doppler beats as a result of a conversion of sinusoidal oscillations to exactly defined sharp pulses which are well suited to evaluation affords a high degree of precision in the frequency range Δf = 15 Hz - 1.5 MHz. It also permits a focusing of time- or location-dependent record markings or the concentration of the Doppler beat through these markings.

The supplement will discuss measuring methods for determining the effective actual barrel wavelengths Λ during firing for free space waves λ_0 = 30.626 mm (X band) and λ_0 = 8.56 mm (Q band) and the measurement results.

1. Introduction

Report 8/64 relates to interior ballistics measurement methods and describes the results obtained with the specified apparatus. A substantial part of these experiments is concerned with determination of path and time characteristics of the shot in the bore through application of the Doppler radar principle. In the limits of this work, an exact description of the circuitry of the measuring apparatus was not possible.

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*Numbers given in margin indicate pagination in original foreign text.

Moreover, since substantial parts of the measurement setup are of /6
interest for other measurements in the broadest sense, a report will be presented here concerning some important apparatus and their circuits. In addition, changes in circuits of commercially available apparatus will be described.

The basis is the block diagram of Report 8/64, which is reproduced with some additions as figure 1 of this paper.

2. Recording Amplifier

The heavily outlined units in figure 1, designated by the letters A, B, C, D, F, G, are combined to a closed unit, designated recording amplifier (see block diagram fig. 2). This amplifier permits:

2.1. Amplification of sinusoidal frequencies (units $D_1 + D_2$). The bandwidth is Δf = 15 Hz-1.5 MHz at a maximum amplification factor of 2500. Maximum output voltage $U_a \approx 3\ V_{eff}$ (output (a));

2.2. Conversion of sinusoidal oscillations to rectangular oscillations, and after differentiation, the creation of positive pulses. The rise time of the pulse front is 0.5 µsec, the half width is ~ 2 µsec and amplitude is ~ 4.5 V (Δf = 15 Hz-300 kHz) (output (b));

2.3. Focusing of two independent, locally and temporally determined markings on the pulsed output (b). By short-circuiting inputs I and II, 5 V potential jumps are created in stages A' and B', which control the bistable sweep stages A and B. Corresponding potentials are in turn derived from these /7
for control of gate G.

By short circuit of input I, gate G, normally closed, is opened so that thereafter the pulses developed in the Schmitt trigger F can be taken off over the matching stage G'. A short-circuit at input II closes gate G and blocks the output (b).

Both markings (short-circuits over inputs I and II) thus allow a localization of a specific measuring process.

2.4 The creation and transmission of control and marking pulses which are taken off from short-circuits at inputs I and II.

At input (c) there is obtained a pulse derived from input I, with +40 V peak voltage, a front width of 0.2 µsec and a half-width of 3 µsec at an output impedance of about 100Ω. (For the time being this pulse serves to trigger the X-ray flash apparatus.) Output (d) delivers two pulses derived from inputs I and II with a peak voltage of +15 V.

Since the start and stop stages block each other, the correct succession of pulses is ensured (K II after K I).

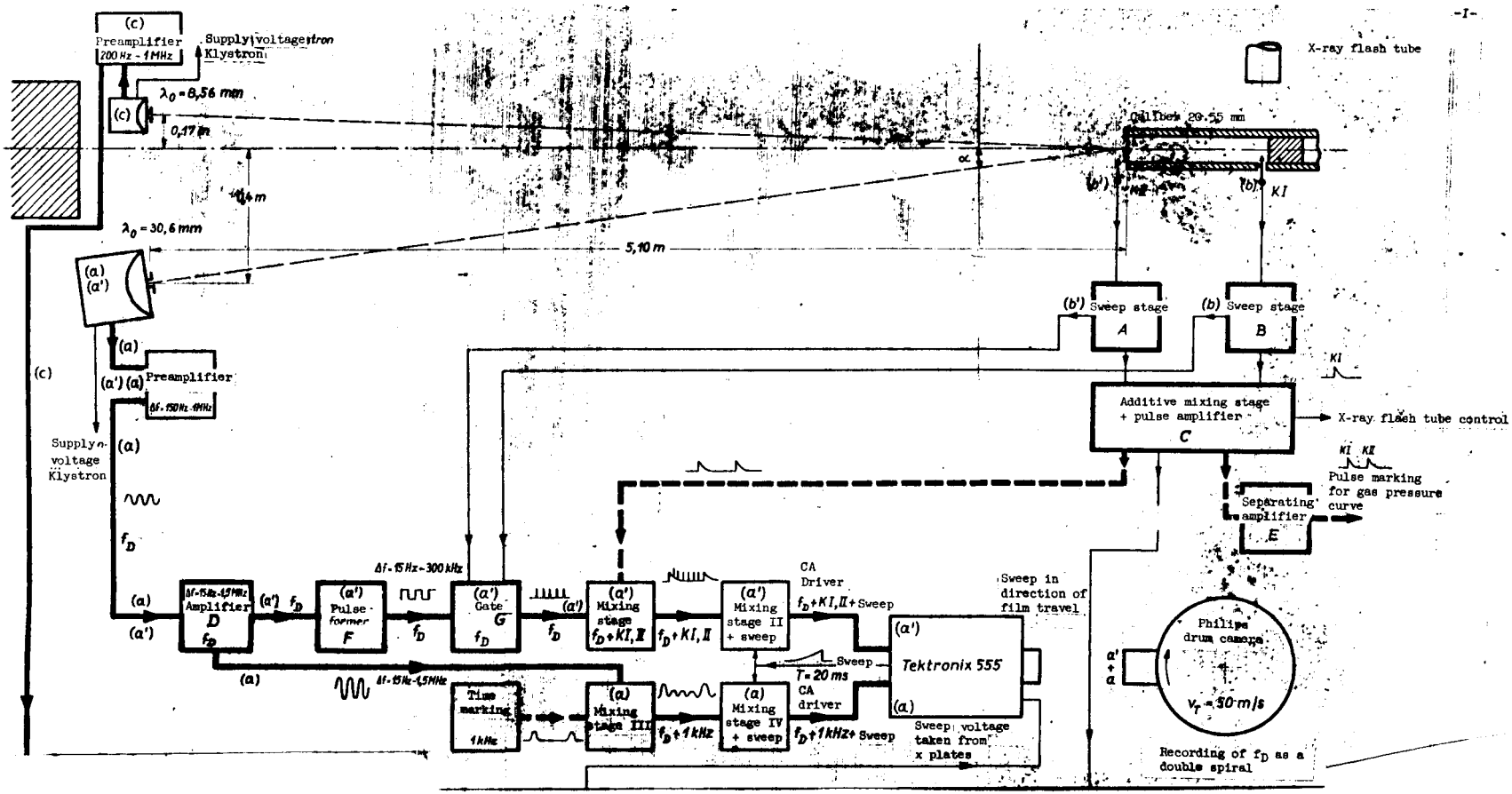

Figure 1. Block diagram of the Doppler ISL measuring and recording apparatus for interior ballistic measurements at caliber 20.55 mm; λ_0 = 30.626 mm and 8.562 mm.

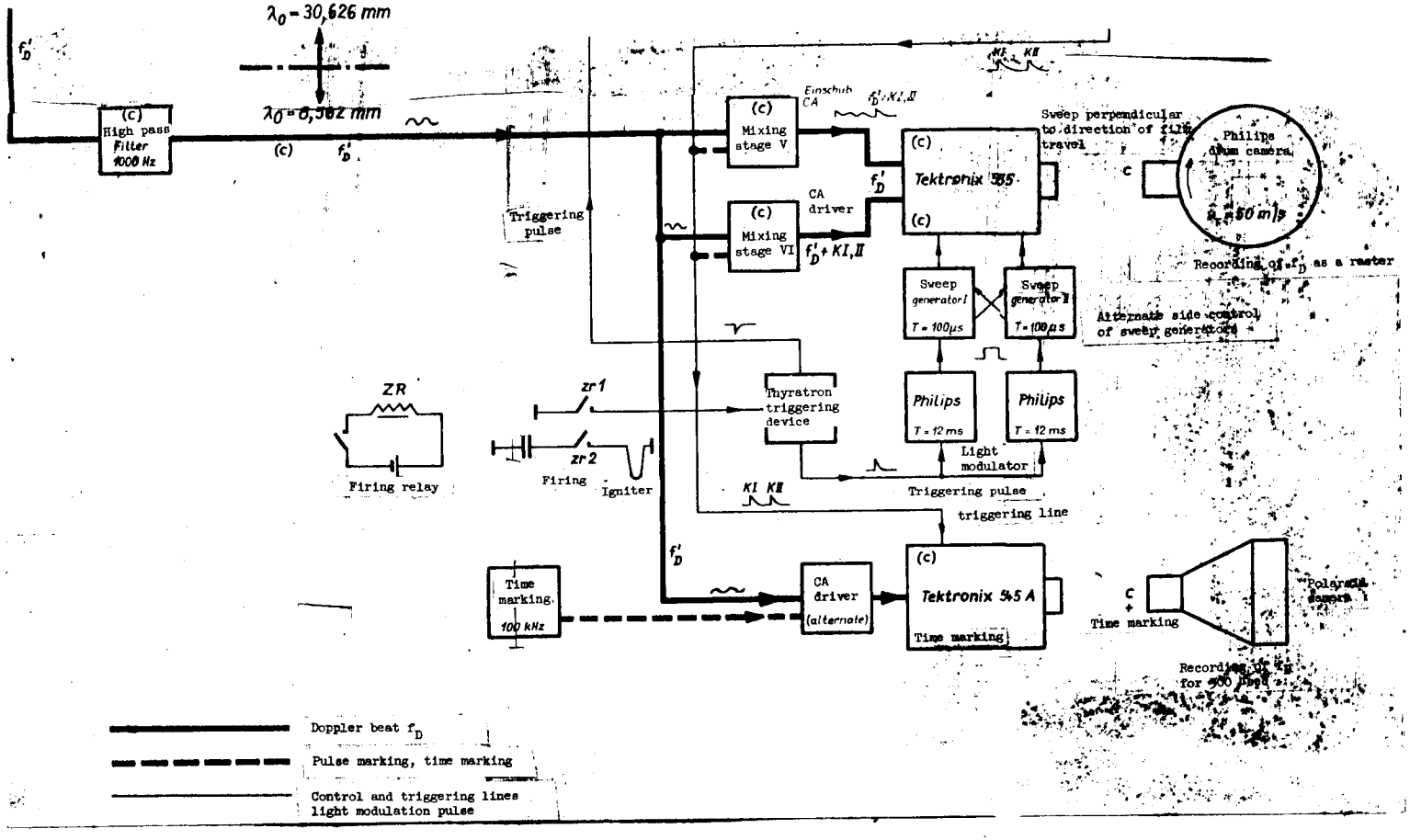

Figure 1. (continued).

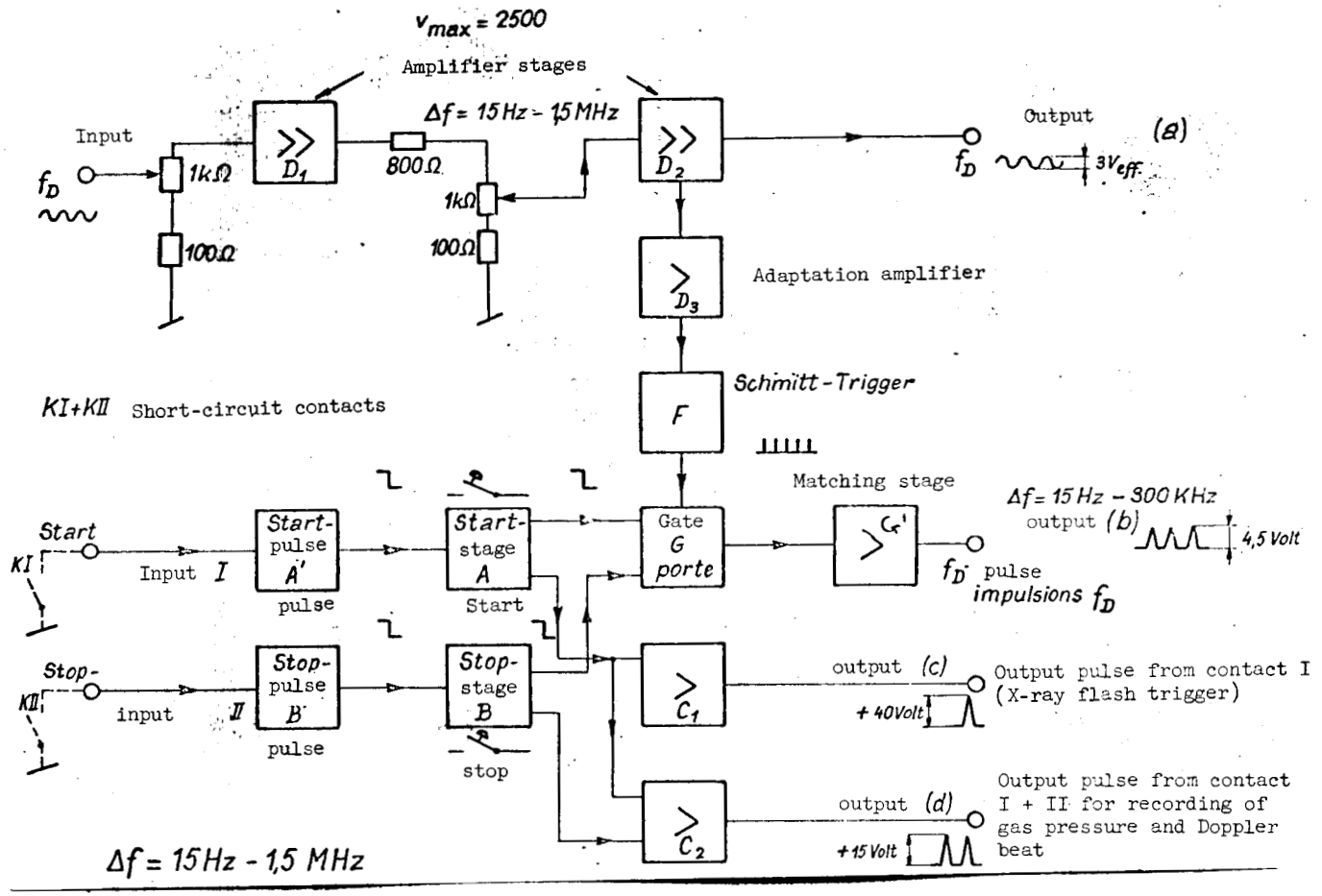

Figure 2. Block diagram of the recording amplifier for interior ballistic measurements.

Figure 3 presents the exact circuit diagram of the amplifier.

As far as possible, units of the Labor amplifier developed at ISL were used.[1] Figure 4 shows a photograph of the device. Figure 5 presents the frequency characteristic.

3. Notes on Mixing Stages I to VI (fig. 1)

For recording of the Doppler beats of the X band radar in the form of /8
a spiral, a superposition of three processes is necessary for each beam of the dual beam oscillograph (Tektronix 555).

Beam 1: Doppler pulse + start-stop pulse + sweep 20 msec

Beam 2: Doppler beat + time marking + sweep 20 msec

The sweep (20 msec) shifts the cathode ray beam perpendicularly to the film runoff during the recording process.

For superposition of two processes the model amplifier CA alternate (Tektronix Dual Trace) is advantageous if it is used not as an electronic switch but rather as an additive mixing stage. Mixing stages II, IV, V and VI are developed by these alternates (CA).

Two further simple mixing stages, here designated I and III in figure 1, must be set up; their circuits are illustrated in figures 6 and 7. The operating voltage for these transistorized circuits is taken from the recording amplifier.

4. Notes on the Recording Oscillographs (Tektronix 555)

Of course, Tektronix oscillographs cannot be light-modulated for periods of several milliseconds or even seconds without circuit changes. The light-modulation capability provided for these oscillographs (via the cathode) is only intended for short time markings (μsec) and furthermore requires a high voltage pulse that is not always available.

However, there is the following simple method of light-modulating the beam or beams of the cathode ray device for periods up to 10 sec.

The built-in sweep generator is used in the "single-sweep" setting, /9
and the gate (light modulation pulse) controls the intensity of the cathode ray beam via the Wehnelt cylinder. However, the deflection voltage leading to the x plates is cut off. Thus there results a simple possibility for light modulation by separation of a single connection, without additional apparatus.

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[1] An adaptable transistorized amplifier of standardized plug-in circuitry units (G. Schultze: ISL Aktennotiz N 19/62).

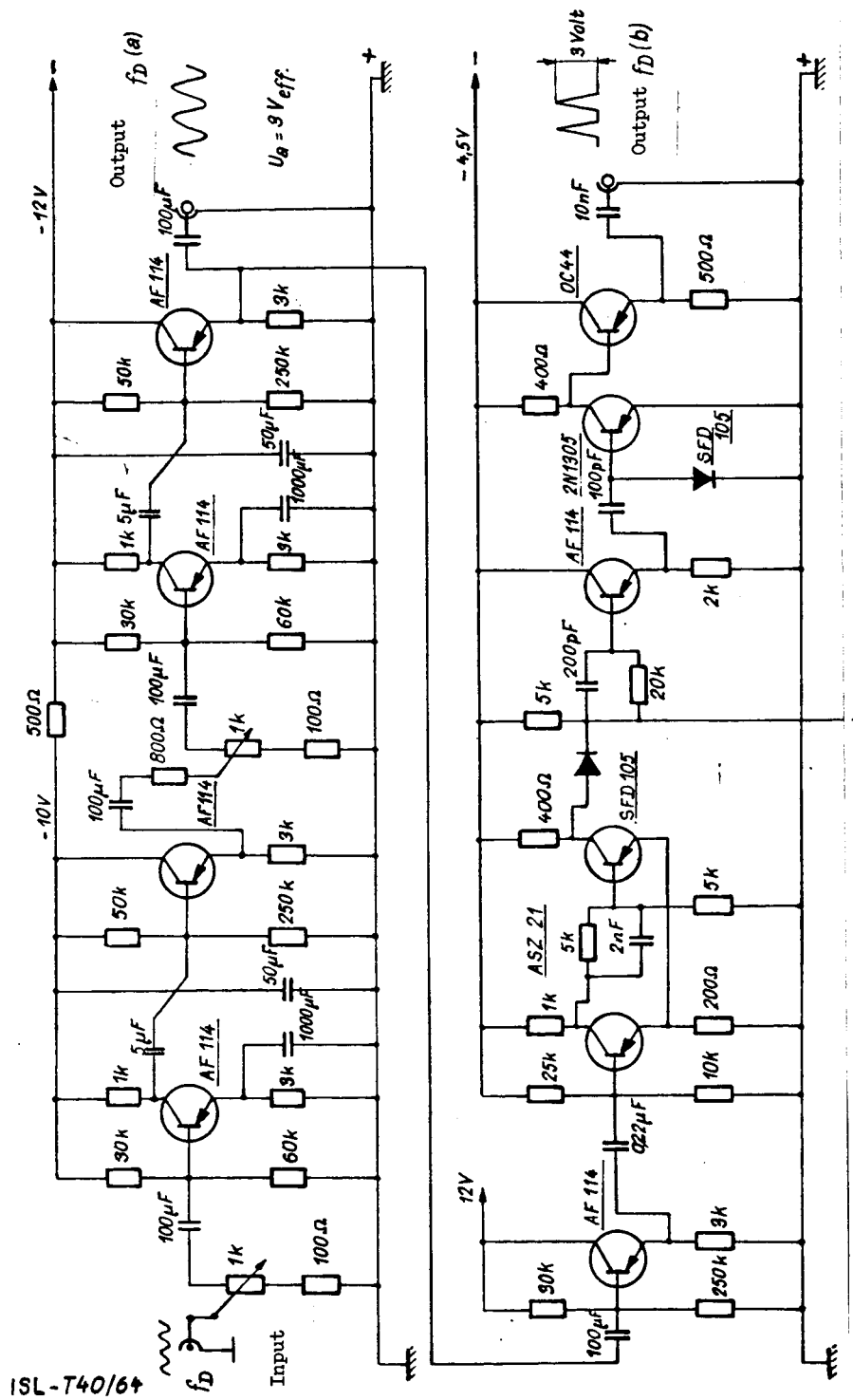

Figure 3. Circuit diagram of the recording amplifier.

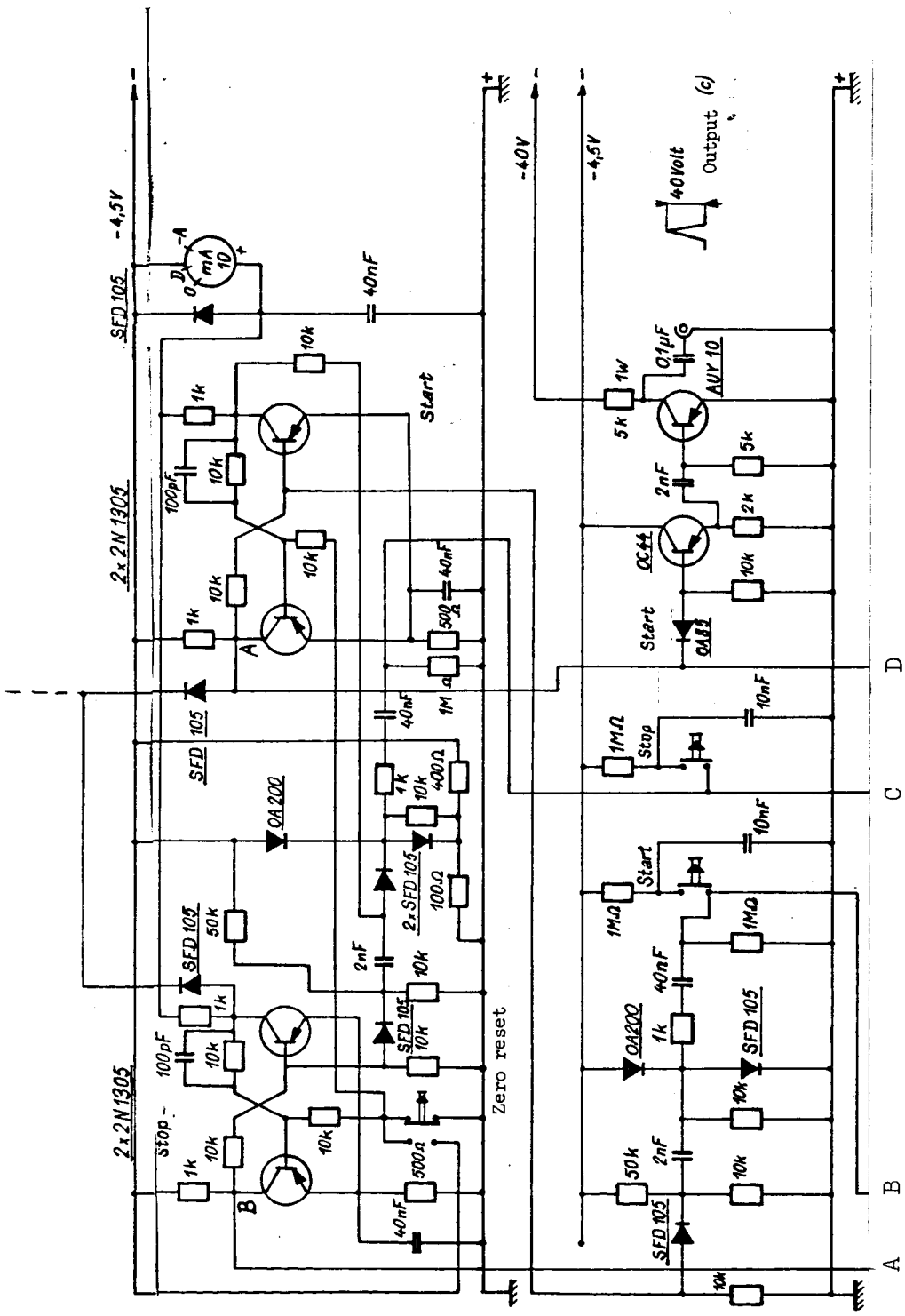

Figure 3. (continued).

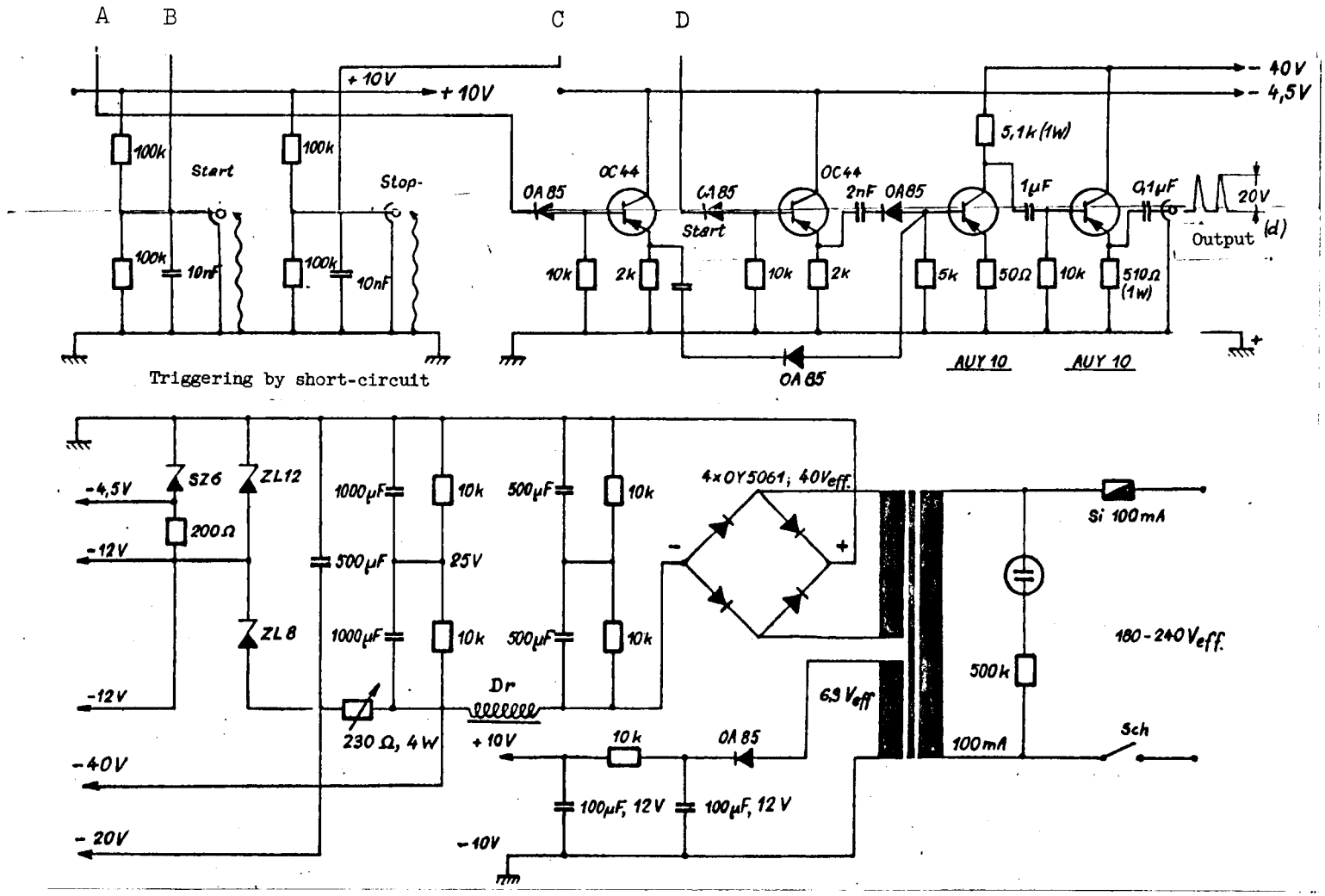

Figure 3. (concluded).

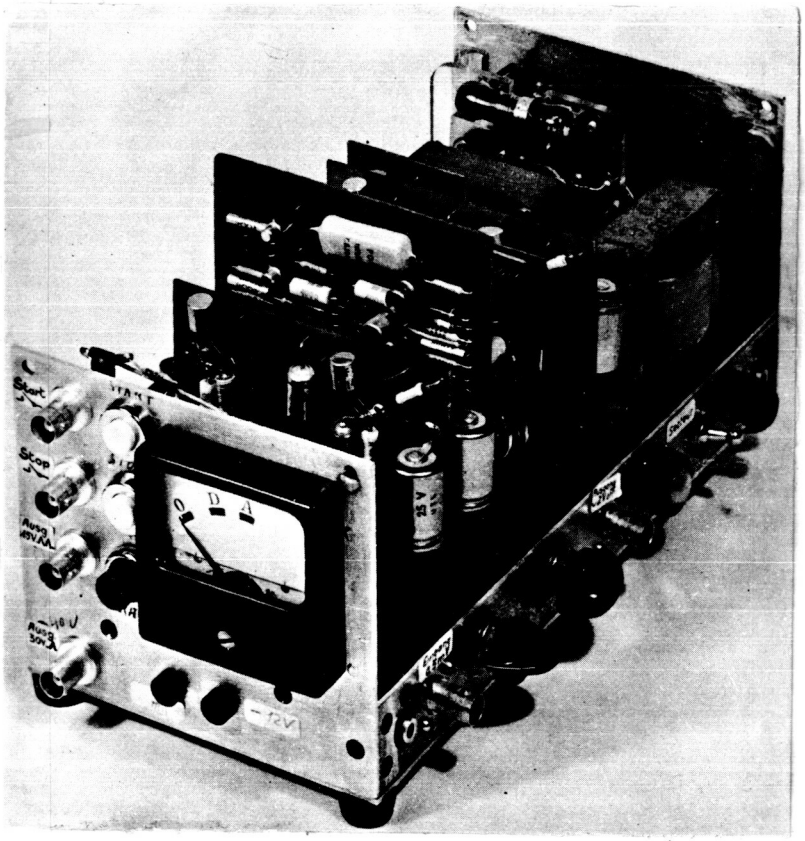
Input
Output (d) + gas pressure measuring apparatus
Output
f_D sinusoidal
Amplification control
Output (c): control of the flash radiography apparatus
Input f_D
Output (b): f_D (as pulses) at the back of the apparatus

Figure 4. Recording amplifier.

Separation occurs at the "horizontal display switch" (connection of switch and horizontal amplifier).

With a recording film velocity of 50 m/sec (motion of travel in the x plate direction instead of the sweep voltage) with an oscillation interval of 0.5 mm, a frequency of 100 kHz can still be well evaluated on the film.

However, for recording of the Doppler beat with introduction of Q band radar (8.6 mm wavelength) the recording range is insufficient for f_D = 100 kHz.

The Doppler beat frequency up to f $\approx$ 250 kHz can only be recorded by means of a raster on the running film. A practically uninterrupted raster results if the two time-deflection generators of the Tektronix model 555 oscillograph are allowed to operate alternately in mutual dependence and if each generator is associated with a cathode ray beam of the dual beam oscillograph. The triggering of one time base always occurs through the backward flank of the corresponding gate of the other time generator. The process to be received and investigated

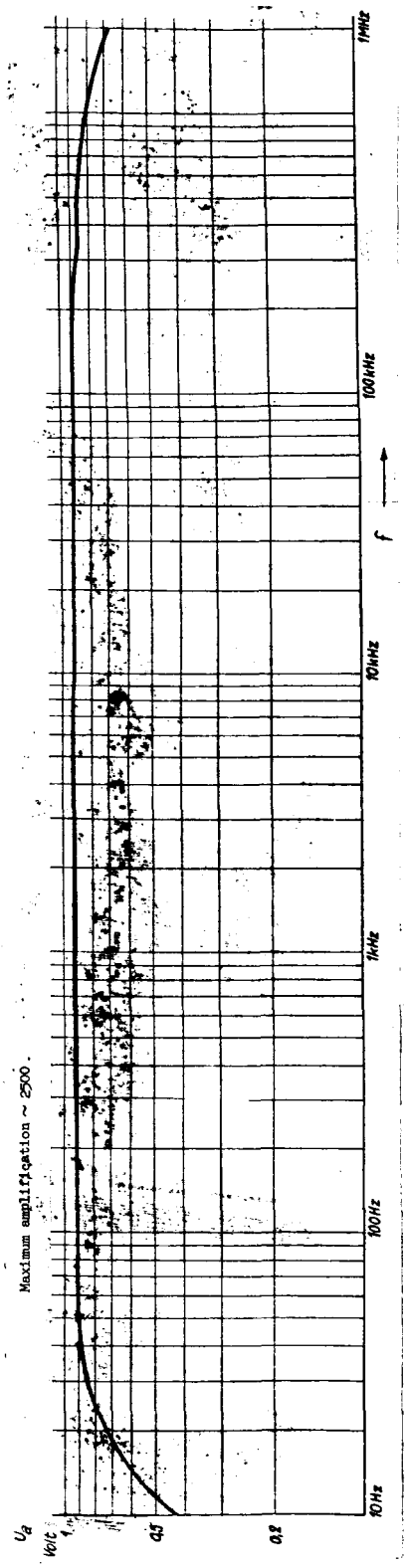

Figure 5. Frequency characteristic of the recording amplifier.

is connected in parallel in the y direction to both input amplifiers. The switch-over time of the sweep generators is about 0.2 μsec, independent of the set sweep times. The recording film moves perpendicularly to the time deflection. Frequencies of f_D = 1 MHz are measurable, with a film velocity of 50 m/sec, an image scale of 3-1, a measuring amplitude on the screen of ~6 mm and a sweep duration of 100 μsec, for the time of one drum rotation (12 msec). /10

To prevent double exposure, both sweep generators or their positive control pulses for light-modulation of the cathode ray device beam that are dependent upon sweep duration have superimposed on them a supplementary positive nonrecurrent pulse that is controlled by the process itself, corresponding to one rotation interval of the drum (for v_{drum} = 50 m/sec the pulse duration is T = 12 msec).

For good decoupling of the sweep generators, we used two commercially available Philips PP1081 light modulators, both controlled by a thyratron triggering device. The coupling of the light-modulator pulse to the sweep generators occurs with low capacitance via a 0.1 μF capacitor and a 70 kΩ series resistor with a 1V amplitude on the tube grid (V 193A (1/2 6DJ8)).

5. General Information on the Transistorized Preamplifiers in the HF Heads

Two kinds of preamplifiers are used.

5.1. Amplifier with electric coupling of the mixed crystal (fig. 8). The bandwidth is Δf = 5 Hz-1 MHz and the amplification factor is 50.

With this arrangement there is an effective bandwidth Δf ≈ 15 Hz-1 MHz from the HF head to the oscillograph (current

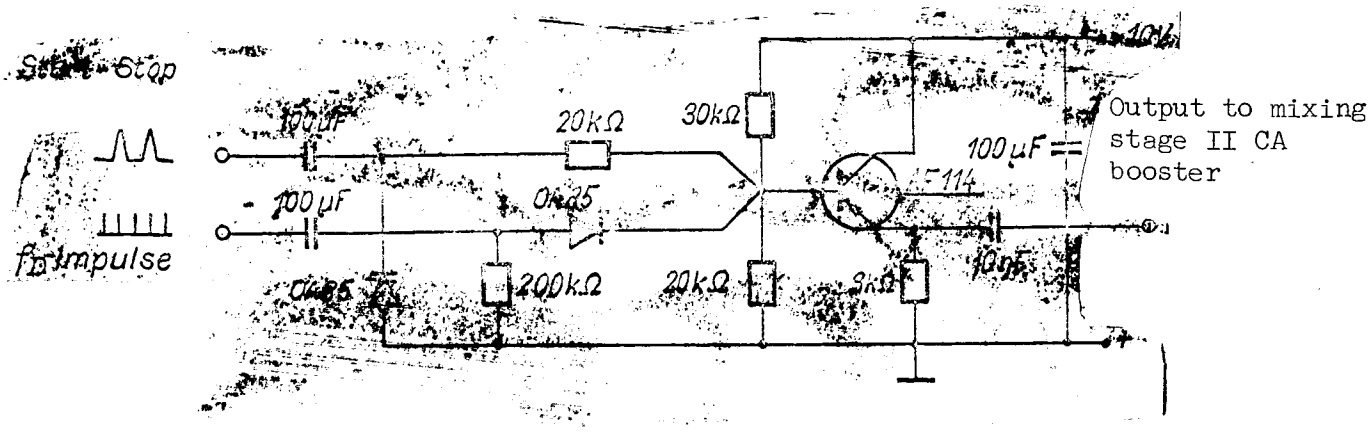

Figure 6. Mixing stage I. Superposition of Doppler pulses and start-stop pulses.

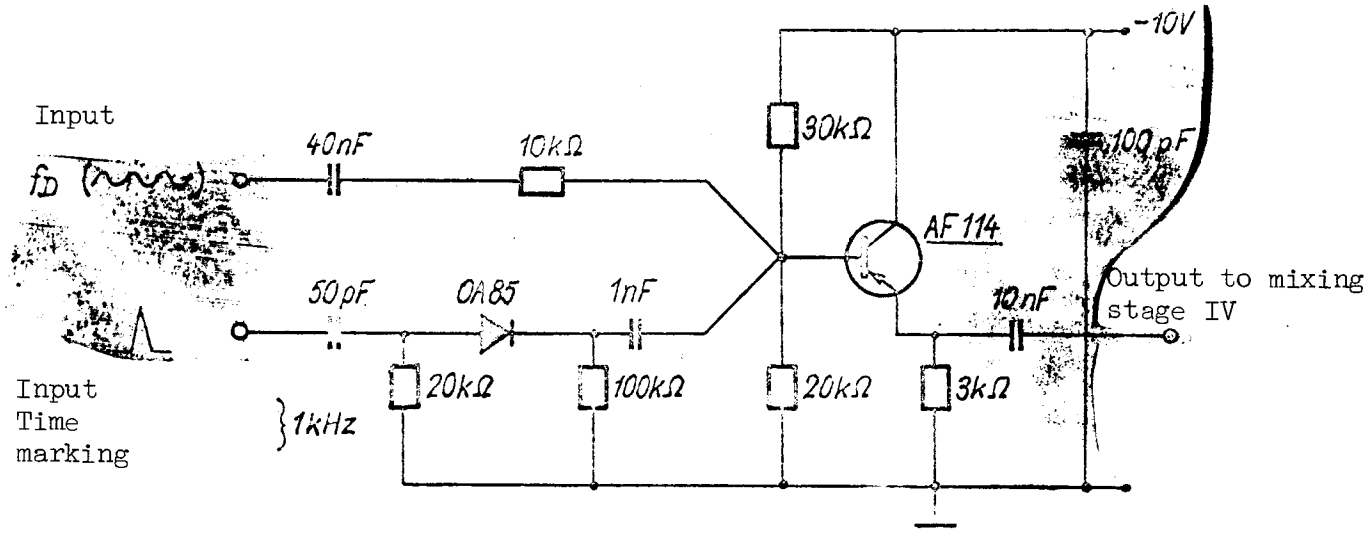

Figure 7. Mixing stage III. Superposition of Doppler beat f_D and time marking 1 kHz.

characteristic (a) in figure 1). Of course, recording on this bandwidth afforded true reproduction of the first phase of movement due to the very low lower frequency limit. However, there was considerable noise stemming /11 from movements of the weapon and other objects upon detonation. Since the effective reflection cross section of the weapon is much greater than that of the projectile, there were very high noise levels which led to complete saturation of the amplifier (D) so that the Doppler frequency signal f_D to be recorded was no longer effective.

Furthermore, it appears that after a projectile movement of $\Lambda/2$ (half the barrel wavelength) the resulting Doppler beat frequency f_D is already

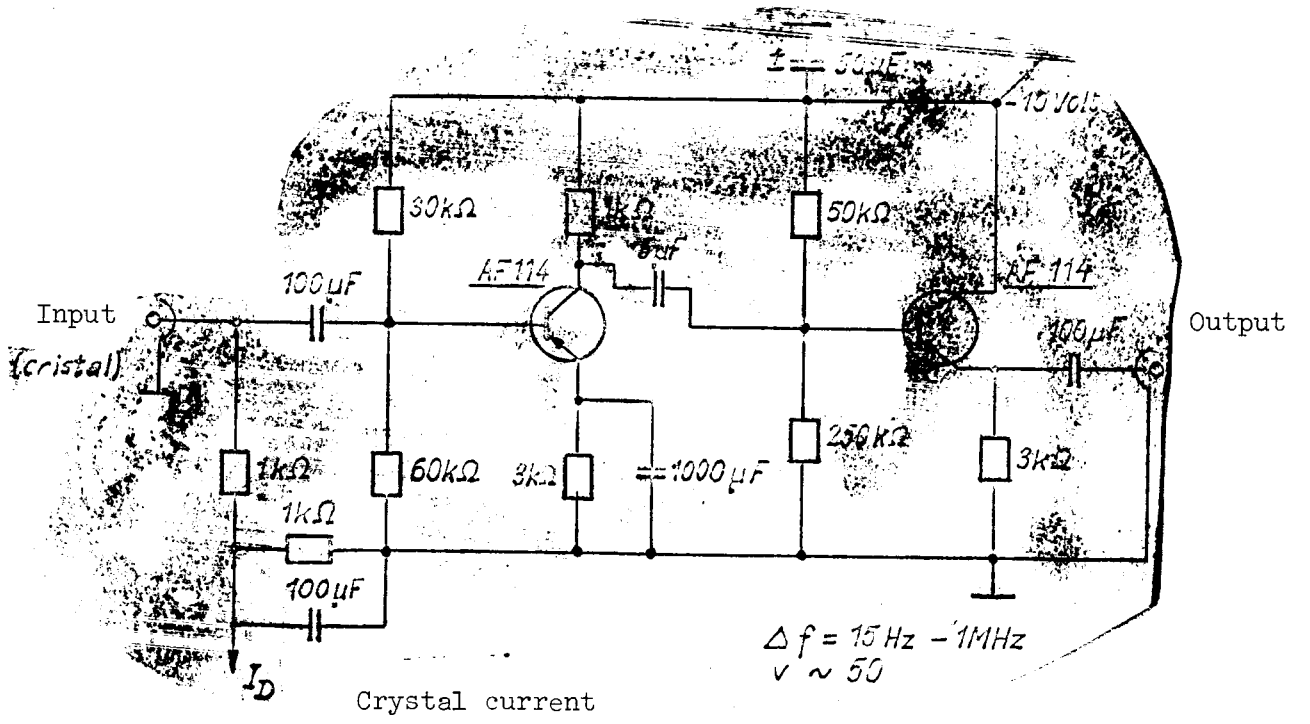

Figure 8. Preamplifier circuit: dc coupling of crystal mixer.

substantially greater than 1000 Hz. It must further be established that even at a lower amplifier limit frequency of 15 Hz the start of the projectile motion at v = 0 or f = 0 cannot be correctly reproduced. Due to this, the true reproduction of the projectile movement in the first half wavelength in the barrel was abandoned. Consequently the lower limit frequency could be raised to ~150 Hz.

5.2. Preamplifier with transformer coupling

There is thus obtained the preamplifier input circuit of figure 9: Δf = 150 Hz-250 kHz, amplification about 150. The transformer also affords a favorable matching of the mixed crystal impedance at the amplifier input and thereby a higher degree of sensitivity of the measuring apparatus.

Supplement

Determination of the effective wavelength Λ in the bore for the free space wavelength λ_0 = 30.626 mm (X band) and λ_0 = 8.65 mm (Q band). /12

Under the present conditions of a smooth bore, for the 3 cm wave the wavelength Λ developing in the bore can theoretically be exactly calculated because according to the condition of exclusion

$$1.31 < \lambda_0/D < 1.71$$

in this case the H_{11} wave can exist as the single wave type.

This exclusivity is not assumed for the excitation with 8.6 mm beam, although experimental results yield a wavelength that is not substantially different from the theoretical H_{11} wave.

1. Theoretical Calculation of Barrel Wavelength

1.1. Frequency f_0 = 9.785 GHz (X band)

From this, with

$c = 2.99680 \cdot 10^{10}$ cm/sec for 70 percent air humidity and

$\lambda = \frac{c}{f_0}$ t = 20°C

λ_0 = 30.626 mm in air.

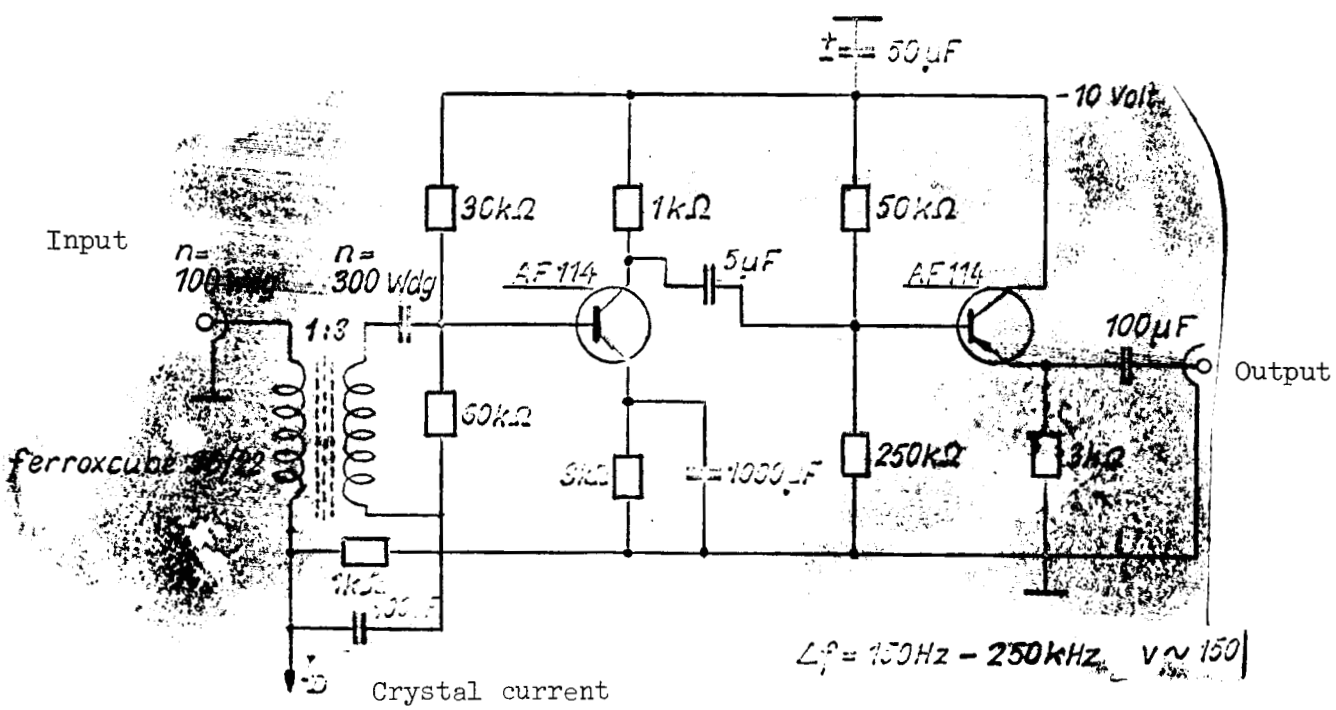

Figure 9. Preamplifier circuit: transformer coupling of the crystal mixer.

For the H_{11} wave in the barrel, with $\epsilon = 1$,

$$\Lambda = \frac{\lambda_0}{\sqrt{1-(\lambda_0/\lambda_g)^2}},$$

Limit wavelength $\lambda_g = 1.70629 \cdot D$.

With D = 20.55 mm,

$$\lambda_g = 35.064 \text{ mm},$$

correspondingly /13

$$\Lambda = 62.892 \text{ mm}$$

or

$$\Lambda/2 = 31.446 \text{ mm}$$

1.2. Frequency $f_0 = 35.0$ GHz (Q band)

With $c = 2.99680 \cdot 10^{10}$ cm/sec

$$\lambda_0 = \frac{c}{f_0} = 8.5623 \text{ mm in air.}$$

For the H_{11} wave in the barrel, with D = 20.55 mm and

$$\lambda_g = 35.064 \text{ mm}$$

$$\Lambda = \frac{\lambda_0}{\sqrt{1-(\lambda_0/\lambda_g)^2}} = 8.8296 \text{ mm}$$

or

$$\Lambda/2 = 4.4148 \text{ mm.}$$

2. Experimental Determination of Barrel Wavelength

2.1. λ_0 = 30.626 mm (X band)

If the exact geometric path of the projectile in the bore is determined and divided by the number of beat maxima occurring during passage of the projectile, the effective barrel wavelength is determined.

The projectile path is defined as the distance between contacts (contact I and II), determined exactly at l = 1575 mm.

On the other hand, the number of beat maxima can be determined from the recordings, and multiplication by half the theoretical barrel wavelength $\Lambda/2$ gives a theoretical contact distance l', which is presented in table I from eight evaluated photographs (column 2). In column 3 the difference Δl = $l - l'$ is established. Column 4 shows error in percent. /14

From the results in table 1 we obtain an average deviation

$$\Delta l = -6.6 \text{ mm or } \Delta l = -0.419 \text{ percent.}$$

With these values the theoretically calculated wavelength Λ can be corrected, and there is obtained an effective wavelength Λ' in the barrel

TABLE 1.

Shot No. 1	l' mm 2	Δl mm 3	Δl % 4
96	1567,2	- 7,8	- 0,5
97	1569,1	- 5,9	- 0,4
98	1570,4	- 4,6	- 0,3
99	1567,0	- 8,0	- 0,5
100	1569,0	- 6,0	- 0,4
101	1571,6	- 3,4	- 0,2
102	1563,3	- 12,7	- 0,8
103	1570,4	- 4,6	- 0,3

$$\Lambda'/2 = 31.4525 \cdot 1.00419 = 31.584 \text{ mm.}$$

With this value $\Lambda'/2$, the overall evaluation was effected.

2.2. $\lambda_0 = 8.56$ mm (Q band)

The corresponding values for the shorter wave $\lambda_0 = 8.56$ mm are presented in table II.

As effective wavelength in the bore we have /15

$$\Lambda'/2 = 4.41478 \cdot 1.00757 = 4.4482 \text{ mm.}$$

This value was also used for the evaluation.

3. Determination of the Wavelength from Static Measurements
Ed. by B. Koch, of Stein

The barrel wavelength was statically determined by means of a caliber-maintaining metal plunger shifted above 45 resonance maxima.

From these measurements we have

TABLE 2.

Shot No. 1	l' mm 2	Δl mm 3	Δl % 4
96	1560.4	-14.6	0.9
97	1564.3	-10.7	0.65
98	1563.8	-11.2	0.7
99	1562.8	-12.2	0.77
100	1563.3	-11.7	0.75
101	1563.8	-11.2	0.7
102	1563.7	-11.3	0.7
103	1562.8	-12.3	0.77

Average error:
$\Delta l = -11.9$ mm
or
$\Delta l = -7.56‰$

3.1. X band

From five measurements for the H_{11} wave there results the limit wavelength λ_g

$$\lambda_g' = 35.088 \text{ mm}.$$

This statically determined value $\lambda_g' = 35.088$ mm deviates from the theoreti- /16
cal value for D = 20.55 mm, which was $\lambda_g = 35.064$ mm.

If now from the found value, $\lambda_g' = 35.088$ mm is used as a basis for calculation of the effective barrel diameter, we obtain

$$D' = 20.564 \text{ mm } \phi.$$

A check of the barrel diameter at the bore carried out on the basis of this result produced at a length of 85 mm from the muzzle a diameter of D = 20.563 mm. It was possible to demonstrate by means of the caliber-maintaining mandrel that this diameter remains unaltered to 60 mm ahead of the cartridge chamber, where the diameter enlarges to D = 20.603 mm ϕ.

It is thus demonstrated that the theoretically calculated value agrees with the statically obtained value.

The effective wavelengths in the bore following the shot experiments can be brought into agreement with the theoretically and statically tested wavelengths only with the following assumptions:

1) The effective barrel diameter before the shot narrows during the shot to $D_{eff} = 20.52$ mm, i.e., by about 40μ.

2) The dielectric constant of the gas volume before the shot is less than 1 ($\epsilon = 0.9971$), which can be explained by the presence of ionized powder gas.

3.2. The static measurements in the Q band ($f_0 = 35$ GHz) yield:

Barrel length measured above 100 maxima: $l' = 433.8$ mm (average of 4 measurements);

Barrel length determined from the theoretical wavelength above 100 oscillations: /17

$$l = 430.8 \text{ mm}.$$

Thereby $\Delta l = \overline{l'} - l = 3.0$ mm or $\Delta l = 7^{\circ}/_{oo}$.

This deviation cannot be explained by any of the assumptions of section 3.1. (The effective barrel diameter under the assumption of an H_{11} mode had to amount to about 18.5 mm.) Presumably the simultaneous excitation of high modes of oscillation is responsible for the difference. Notably, this time there is a good correlation of the static measurements with wavelengths determined from the shot. It can therefore be assumed that the cause of the deviation is the same in both cases.

Translated for the National Aeronautics and Space Administration
by John F. Holman and Co. Inc.